A Primer on *ZEUS-3D*

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Prerequisite: A PRIMER ON MAGNETOHYDRODYNAMICS, by DAC.

Contents

1 What is *ZEUS-3D*?

You don't really understand something until you can compute it.

Michael L. Norman, *Director, SDSC*

ZEUS-3D is a multi-physics, covariant, computational fluid dynamics (CFD) *FORTRAN77* code designed primarily for, but not restricted to, astrophysical applications. It was born from the *ZEUS*-development project headed by Michael Norman at the NCSA between 1986 and 1994 whose principal goal was to develop a robust, user-friendly, multi-purpose MHD code that could be released as open-source with full documentation. Principal developers other than DAC and MLN have included Jim Stone and Robert Fiedler and, over the years, various versions of the code have become publicly available. However, only the ICA version has had any significant algorithm development since 1995, and it is this version that is the subject of this primer.

ZEUS-3D includes the effects of magnetism, self gravity, viscosity, a second cospatial and diffusive fluid, molecular cooling, and can be run with an isothermal, adiabatic, or polytropic equation of state. Terms in equations (1)–(6) below are colour-coded respectively; black terms being the standard equations of ideal HD. Simulations may be performed in any of Cartesian (`XYZ`), cylindrical (`ZRP`), or spherical polar coordinates (`RTP`), and in any dimensionality (1-D, $1\frac{1}{2}$-D, 2-D, $2\frac{1}{2}$-D, or 3-D). The set of equations solved are:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho\, \vec{v}) = 0; \tag{1}$$

$$\frac{\partial \vec{s}}{\partial t} + \nabla \cdot \Big(\vec{s}\vec{v} + (p_1 + p_2 + p_B)\,\mathsf{I} - \vec{B}\vec{B} - \mu\,\mathsf{S} \Big) = -\rho\,\nabla\phi; \tag{2}$$

$$\frac{\partial e_1}{\partial t} + \nabla \cdot (e_1 \vec{v}) = -p_1 \nabla \cdot \vec{v} + \mu \mathsf{S} : \nabla \vec{v} - \mathcal{L}; \tag{3}$$

$$\frac{\partial e_2}{\partial t} + \nabla \cdot (e_2 \vec{v} - \mathsf{D} \cdot \nabla e_2) = -p_2 \nabla \cdot \vec{v}; \tag{4}$$

$$\frac{\partial e_{\mathrm{T}}}{\partial t} + \nabla \cdot \Big[(e_{\mathrm{T}} + p_1 + p_2 - p_B)\vec{v} - \mu \mathsf{S} \cdot \vec{v} - \mathsf{D} \cdot \nabla e_2 + \vec{E} \times \vec{B} \Big] = -\mathcal{L}; \tag{5}$$

$$\frac{\partial \vec{B}}{\partial t} + \nabla \times \vec{E} = 0, \tag{6}$$

where:

ρ	is the matter density;
$\vec{v}$	is the velocity;

$\vec{s}$	is the momentum density $= \rho\vec{v}$;
p_1 & p_2	are the partial pressures from the first and second fluids;
p_B	is the magnetic pressure $= \frac{1}{2}B^2$;
I	is the unit tensor;
$\vec{B}$	is the magnetic induction (in units where $\mu_0 = 1$);
μ	is the shear viscosity;
S	is the viscid part of the stress tensor whose elements, S_{ij}, are given by: $$S_{ij} = \partial_j v_i + \partial_i v_j - \tfrac{2}{3}\delta_{ij}\nabla\cdot\vec{v};$$ where ∂_i indicates partial differentiation with respect to the coordinates, x_i, $i = 1, 2, 3$, and where δ_{ij} is the usual "Kronecker delta";
ϕ	is the gravitational potential, $\nabla^2\phi = 4\pi\rho$, in units where $G = 1$;
e_1 & e_2	are the internal energy densities of the first and second fluids;
$\mathcal{L}$	is the cooling function (of ρ and e_1) for nine coolants (HI, HII, CI, CII, CIII, OI, OII, OIII, SII) interpolated from tables given by Raga *et al.* (1997);
D	is the (diagonal) diffusion tensor;
e_T	is the total energy density $= e_1 + e_2 + \frac{1}{2}\rho v^2 + \frac{1}{2}B^2 + \phi$;
$\vec{E}$	is the induced electric field $= -\vec{v}\times\vec{B}$;

and where the ideal equations of state close the system of variables:

$$p_1 = (\gamma_1 - 1)e_1; \qquad p_2 = (\gamma_2 - 1)e_2,$$

with γ_1 and γ_2 being the ratios of specific heats for the two fluids.

2 Source code management and version control

Version 3.6 of *ZEUS-3D* (`dzeus36`) is managed by *EDITOR*, version 2.2 (`edit22`), which comes as part of the `dzeus36.tar` bundle. *EDITOR* provides two primary functions: source code management and version control.

Source code management

ZEUS-3D is one behomoth code (>130,000 lines) which contains every item of physics, geometry, I/O, algorithm, and symmetry option ever developed for it. While this eases navigating within the code for programmers, it would be nice if the compiler didn't need to waste memory or cpu computing unwanted features.

EDITOR acts as a *precompiler* which can "turn on" and "turn off" certain segments of the code before the compiler sees it. To affect this, *EDITOR* commands (heralded by an asterisk `*` in the first column) are peppered throughout the code which allow the user to render the 3-D code a perfectly efficient 2-D code should a symmetry axis be defined. The following is a snippet of coding from the subroutine `SHKSET` illustrating how this is done:

```
 1  *if -def,KSYM
 2         do 40 k=ksm2,kep3
 3  *endif -KSYM
 4  *if -def,JSYM
 5           do 30 j=jsm2,jep3
 6  *endif -JSYM
 7             do 20 i=imin,imax
 8               d (i  ,j,k) = d0
 9               v1(i+1,j,k) = v10
10               v2(i  ,j,k) = v20 * h31b(i) * h32a(j)
11               v3(i  ,j,k) = v30 * h31b(i) * h32a(j)
12  *if -def,ISO
13               e1(i  ,j,k) = e10
14  *endif -ISO
15  *if def,TWOFLUID
16               e2(i  ,j,k) = e20
17  *endif TWOFLUID
18  *if def,MHD
19               b1(i+1,j,k) = b0 * h2ai(i+1) * h31ai(i+1)
20               b2(i  ,j,k) = b20            * h32ai(j  )
21               b3(i  ,j,k) = b30
22  *endif MHD
23  20         continue
24  30       continue
25  40     continue
```

In a file called `zeus36.mac` (§7), one defines the desired *EDITOR macros* such as `KSYM`, `JSYM`, `ISO`, `TWOFLUID`, and `MHD` illustrated in this segment. Should `MHD` be listed among those defined, lines 19–21 are retained in the compiler copy of the code and thus compiled. Otherwise, these lines are dropped (as are all other mentions of the magnetic field throughout the code), and the magnetic field arrays are not even declared. In a non-MHD simulation, it would be wasteful indeed if one still had to declare three unwanted arrays, fill them with zeroes, and then push around zeroed magnetic fields throughout the simulation.

Other *EDITOR* macros include those for geometry (`XYZ`, `ZRP`, `RTP`), physics (`GRAV`, `RADIATION`, *etc.*), I/O (`PLT1D`, `RADIO`, *etc.*), algorithm (`MOC`, `RIEMANN`, *etc.*), and compiler (`GFORTRAN`, `IFORT`, *etc.*).

Version control

EDITOR can also manage *change decks*, files separate from the main code in which the user can direct *EDITOR* to delete, add, or change lines in the code before the code is compiled. The master copy of the code is left untouched, and multiple developers can have working change decks until such time when it is decided to *merge* all change decks into the code permanently, creating the next version. Typical syntax is as follows:

```
1  *replace ctran1.130,137
2  c
3  c    b) Interpolate "v1" to zone centres.
4  c
5         call x1fc3d ( v1, v1twid )
6  *delete ttran1.150,155
7  *insert cmoc3.230
8  *if -def,ISYM
```

```
 9          do 10 i=ism2,iep3
10  *endif -ISYM
11             vel1(i) = v1 i,js,ks)
12  10      continue
```

Lines 1, 6, and 7 direct *EDITOR* to replace several lines in subroutine `CTRAN1` with the given lines, delete six lines from subroutine `TTRAN1` (and replace them with nothing), and then insert a do-loop after line 230 in subroutine `CMOC3`. Note that other *EDITOR* directives such as lines 8 and 10 can be included as part of an insertion into the code.

Other EDITOR features

EDITOR can also tidy up sloppy *FORTRAN*, create a numbered text file for a *FORTRAN* 77 code, compare two files, split a code (file) into its constituent modules, and a few other tasks useful in developing large codes.

3 Algorithms

There are a semi-infinite number of ways one can difference differential equations (so that the former tend to the latter as $\delta t \to dt$), and yet not all of them are stable in the realm of finite δt. Over the years, a variety of algorithms have been developed to solve the *differenced* equations of MHD stably, and users of *ZEUS-3D* have the benefit of decades of person years of development and experience.

In broad brush terms, `dzeus36` is a conservative code based on a staggered mesh. It is upwinded in both the entropy and Alfvén waves and stabilised against compressive oscillations (fast and slow waves) by the use of von Neumann-Richtmyer artificial viscosity. Interpolations can be as high as third order, though formally the convergence rate of the code can be as low as first order, depending on how it is configured.

Specific algorithms—many of them unique to *ZEUS-3D*—designed to stave off certain types of numerical instabilities not addressed by the attributes listed above are tabulated below, roughly in chronological order.

1. *Consistent Advection* (CA; Norman, Wilson, & Barton, 1980, ApJ, 239, 968) was invented to prevent numerical drift between mass and angular momentum fluxes in axisymmetic HD simulations, and settled the dispute on whether rotating matter accreting onto a point mass formed a disc or torus (NWB proved it to be a disc).

   CA remains in `dzeus36` to this day, though it has been found to be injurious when applied to the energy equation (Clarke, 2010, ApJS, 1897, 119). Thus, as default, CA is applied only to the momenta.

2. *Constrained Transport* (CT; Evans & Hawley, 1988, ApJ, 332, 659), based on a staggered mesh (§4) is a method by which the magnetic field—when initialised to satisfy $\nabla \cdot \vec{B} = 0$—will always satisfy $\nabla \cdot \vec{B} = 0$ to machine round-off error.

3. *Consistent Method of Characteristics* (CMoC; Clarke, 1996, ApJ, 457, 291) is an algorithm which imposes upwindedness in the Alfvén speed and by which the velocity and

magnetic field required to calculate the induced electric field are interpolated implicitly over a plane, rather than explicitly in one direction at a time. This is necessary to prevent a numerical phenomenon in which a localised weak magnetic field could be promoted by several orders of magnitude in a single time step because of inconsistently determined interpolations.

4. *Finely Interleaved Transport* (FIT; Clarke, unpublished). Certain multi-dimensional problems (*e.g.*, 2-D transport of Alfvén waves) could not be done by any previous version of *ZEUS* without features being broken up into stripes perpendicular to the direction of propagation. FIT cures this problem.

In addition, there are three interpolation algorithms (donor cell, van Leer's second order interpolation, and Colella & Woodward's piecewise parabolic interpolation), three self-gravity algorithms (Successive Over-relaxation, Full Multi-grid, and FFT), and two kinds of artificial viscosity (von Neumann-Richtmyer algorithm of 1950, and a tensor algorithm).

4 Staggered mesh

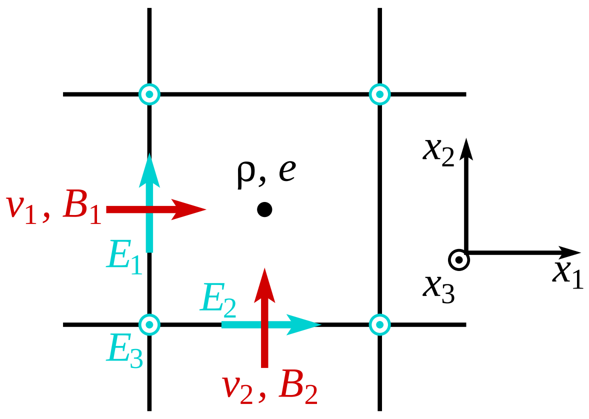


Figure 1: The staggered mesh depicted in the 1-2 plane.

ZEUS-3D is based on a staggered mesh as shown in Fig. 1. Scalars (ρ, e; black) are *zone-centred*, primary vector components ($\vec{v}$, $\vec{B}$; red) are *face-centred*, and derived vector components ($\vec{E}_{\rm ind}$; cyan) are edge-centred.

Two main benefits of using a staggered mesh are flux computation and preserving $\nabla\cdot\vec{B}=0$. On the former, consider the differenced continuity equation when $\vec{v}=v_1\hat{x}_1$:

$$\frac{\rho_i^{n+1}-\rho_i^n}{\delta t^n} = -\frac{\rho_{i+\frac{1}{2}}^{n+\frac{1}{2}}v_{1,i+1}^n - \rho_{i-\frac{1}{2}}^{n+\frac{1}{2}}v_{1,i}^n}{\delta x_i},$$

where superscripts indicate time step, subscripts zone number, and where the half super/sub-scripts indicate some sort of time-centring/spatial interpolation. This equation can then be solved for ρ_i^{n+1}, the value of ρ at zone i at the next time step.

Evidently, the fluxes (ρv) are computed at the zone faces ($i\pm\frac{1}{2}$). To do this, the zone-centred ρ must be interpolated to the zone faces, a time-consuming effort fraught with a host of numerical "landmines". On the other hand, face-centred v_1 (by virtue of the staggered mesh) need not be interpolated, providing significant computational relief.

More significant is the preservation of $\nabla\cdot\vec{B}=0$ (the *solenoidal condition*). Consider the evolution of B_1 and B_2 with 3-symmetry where the 1- and 2-components of the induction equation are:

$$\frac{\partial B_1}{\partial t} = \frac{\partial E_3}{\partial x_2}; \qquad \frac{\partial B_2}{\partial t} = -\frac{\partial E_3}{\partial x_1}$$

since the 3-derivatives are zero. Differencing this (with the 3-component of the induced electric field, E_3, located at the 3-edges as shown in Fig. 1 with the cyan circle-dots), we get:

$$\frac{\delta B_{1,i,j}}{\delta t} = \frac{E_{3,i,j+1} - E_{3,i,j}}{\delta x_2}; \qquad \frac{\delta B_{2,i,j}}{\delta t} = -\frac{E_{3,i+1,j} - E_{3,i,j}}{\delta x_1}. \tag{7}$$

Taking the differenced divergence of the *changes* in the magnetic field, we get:

$$\nabla \cdot \delta \vec{B} = \frac{\delta B_{1,i+1,j} - \delta B_{1,i,j}}{\delta x_1} + \frac{\delta B_{2,i,j+1} - \delta B_{2,i,j}}{\delta x_2},$$

now a zone-centred quantity. By substituting equation (7) for the δBs, every term on the right hand side cancels identically, and $\delta \vec{B}$ is numerically divergence-free. Thus, if $\vec{B}$ is initialised divergence free, it will remain so to numerical round off error throughout the simulation. I challenge you to place the magnetic field components at the zone-centres, for example, and try to find a way maintain $\nabla \cdot \vec{B} = 0$ to round-off error!

5 Boundary conditions

Boundaries are set independently for each of six grid boundaries and, within each boundary, the boundary *type* may be set zone by zone. Ten boundary types are currently supported:

1. reflecting boundary conditions at a symmetry axis ($r = 0$ in `ZRP`, $\theta = 0$ or π in `RTP`) or grid singularity ($r = 0$ in `RTP`);
2. *non-conducting* reflecting boundary conditions (Fig. 2*a*);
3. *conducting* reflecting boundary conditions (Fig. 2*b*);
4. *continuous* reflecting boundary conditions (Fig. 2*c*);
5. periodic boundary conditions;
6. "self-computing" boundary conditions (for *AMR*);
7. transparent (characteristic-based) outflow boundary conditions (not implemented);

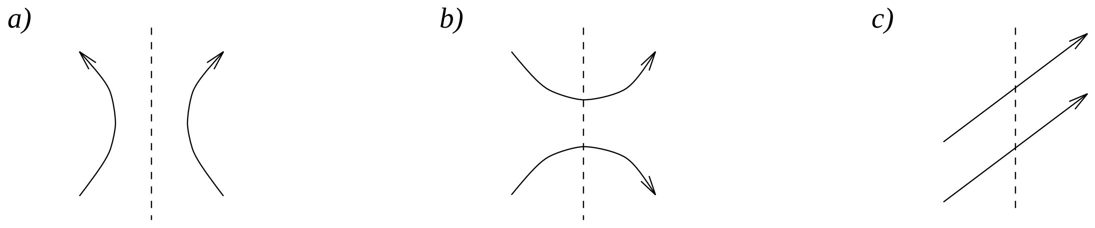


Figure 2: Magnetic field lines across three different types of reflecting boundaries. a) non-conducting boundaries $\Rightarrow$ $B_{\|}(\text{out}) = -B_{\|}(\text{in})$, $B_{\perp}(\text{out}) = B_{\perp}(\text{in})$; b) conducting boundaries $\Rightarrow$ $B_{\|}(\text{out}) = B_{\|}(\text{in})$, $B_{\perp}(\text{out}) = -B_{\perp}(\text{in})$; and c) continuous boundaries $\Rightarrow$ $B_{\|}(\text{out}) = B_{\|}(\text{in})$, $B_{\perp}(\text{out}) = B_{\perp}(\text{in})$. The designations $\|$ and $\perp$ are relative to the boundary *normal*.

8. "selective" inflow boundary conditions (useful for sub-fast-magnetosonic inflow);
9. traditional outflow boundary conditions (variables constant across boundary);
10. traditional inflow boundary conditions (suitable for super-fast-magnetosonic inflow).

All boundary conditions strictly adhere to the solenoidal condition, even where different boundary types adjoin on the same boundary. The first five conditions are *exact*, while the latter five are approximate and can sometimes launch undesired waves into the grid.

6 In-line graphics and I/O

One may request a variety of output to be dumped to disc periodically during a `dzeus36` run. Each format of I/O has its own file-naming syntax of the form `zxvvnnnid.mm`, where:

- the first letter is always `z` to indicate the file came from *ZEUS-2D* or *ZEUS-3D*;
- `x` is one- (occasionally two-) characters to identify the type of output;
- `vv` (when present) is a user-set two-character tag to identify the variable;
- `nnn` is the three digit sequential number of the file;
- `id` is a user-set two-character tag to identify one run from another; and
- `mm` (when present) is a two-digit number to identify the slice.

The principle forms of graphical output include:

1. *1-D line plots*: `zpnnnid.mm` (*e.g.*, left panel of Fig. 3)
   - any number of 77 variables plotted against any of the three coordinate axes
   - variables can be plotted as lines or using one of 6 different symbols
   - one or multiple plots per graph; one or multiple graphs per page
2. *2-D contour plots*: `zqnnnid.mm` (*e.g.*, second left panel of Fig. 3)
   - "buffet-style" plotting: as many as two scalars and three vector fields may be plotted on the same graph
   - scalars plotted as colour or greyscale, and/or lines
   - different vector fields plotted with different colours
3. *2-D pixel dumps*: `zivvnnnid.mm` [*e.g.*, second right panel (top) of Fig. 3]
   - 2-D slices through datacube assembled to an mpeg automatically at run's end
   - any number of 78 variables may be plotted in one or more planes
4. *"RADIO" dumps*: `zRvvnnnid` [*e.g.*, second right panel (bottom) of Fig. 3]

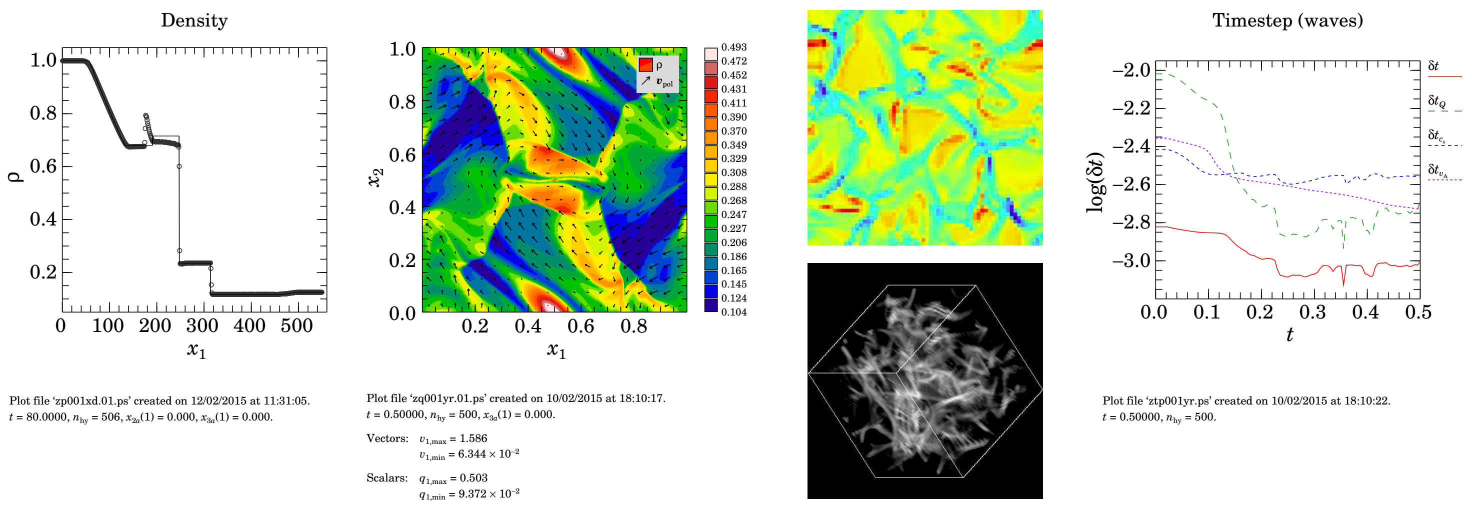


Figure 3: From left to right: 1-D line (bubble) plot of the density in the Brio & Wu shock tube problem; a colour contour plot showing both density and velocity vectors from the Orzsag-Tang vortex; a 2-D pixel plot of the velocity divergence (top) and a line-of-sight integration dump of the synchrotron emissivity in a low resolution (64^3) run of super-Alfvénic turbulence; and a time slice plot showing how the time-steps, δt, evolve over the course of a simulation.

- line-of-sight integrations from an arbitrary and possibly moving vantage point automatically assembled to an mpeg at run's end
- any number of 25 variables to select, including all primitive variables, Stokes I, Q, and U parameters, bremsstrahlung, and a number of other derived quantities.

5. *History plots*: `ztpnnnid` (*e.g.*, right panel of Fig. 3)
    - 97 different variables including variable extrema, time steps, and volume integrals plotted against problem time
    - used to monitor a simulation, track conserved quantities, variable extrema, *etc.*

Other formats of I/O to and from `dzeus36` include:

1. *Input deck* (`inzeus`) is the only input data file *ZEUS* requires, and includes all namelist specifications

2. *Restart dumps* (`zrnnnid`) is an image of the simulation suitable for resuming the simulation from the time the dump was created.

3. *HDF dumps* (`zhvvnnnid`) are HDF4 files of any number of 53 variables, including a "total HDF dump" which includes all primitive variables, suitable for post-processing and graphics (but not a restart).

4. *"Corks"* (`zcnnnid`) are passive particles injected into the flow to keep track of 63 different quantities as functions of time in Lagrangian coordinates.

5. *Logfile* (`zlnnnid`) records namelist choices, grid information, and various terminal messages generated throughout the run.

6. *Display dumps* (`zdvvnnnid.mm`) are 2-D slices of numerical values for any number of 50 variables arranged on a grid with zone indices labelling the horizontal and vertical axes; primarily used for debugging.

Plots shown in this primer are in-line features of `dzeus36`. Some plots may be created after a run by using the post-processing ancillary codes *PLOTZ* and *RADIO*, both included in `dzeus36.tar.gz` with a user manual. The former creates 1-D and 2-D plots, while the latter does line-of-sight integrations at various vantage points through a simulation "still". Both of these codes take "total HDF4 dumps" as their input.

7 Running *ZEUS-3D*

ZEUS-3D is run by preparing two, perhaps three ascii files. These are:

1. user-written change deck(s) to add, modify, or delete code in `dzeus36` (optional);
2. `zeus36.mac`, a "macro file" containing all macros directing *EDITOR* which portions of the code are to be passed to the compiler;
3. `dzeus36.s`, a "script file" containing unix commands that takes care of:
   - assembling all files needed for compilation and linking including libraries, user-written change decks, and `zeus36.mac`;
   - launching *EDITOR* to perform the precompilation steps;
   - launching the makefile created by *EDITOR* to create the executable, `xdzeus36`;
   - creating the input file `inzeus` required by `xdzeus36` to do the calculation.

Once `zeus36.mac`, `dzeus36.s`, and possibly the change deck(s) are prepared as required, they should be placed in their own directory and the command:

```
csh -v dzeus36.s
```

should be issued at the unix prompt. If all goes well, the executable (`xdzeus36`) and input file (`inzeus`) are created in the directory. Typing `xdzeus36` at the prompt then launches the run.

If run in the foreground, `dzeus36` can recognise numerous "interrupt messages" which can be issued at the terminal. These include asking how far along the simulation is, requesting a plot to be generated, changing the length of time the simulation is to run, or even stopping cleanly (or aborting abruptly). The reader is referred to the user manual for details.

For an ideal MHD run and a modest amount of I/O, `dzeus36` is about 95% parallel, which means it can make good use of sixteen processors, but not necessarily 32. *EDITOR* can be directed to prepare both the code and even the user's change decks for a parallel application using OpenMP. In principle, there is very little the user needs to do (other than write thread-safe code) to prepare an executable to run in parallel.

Working examples of `zeus36.mac` and `dzeus36.s` are included in the public domain tarball `dzeus36.tar.gz`, and detailed descriptions are given in the user manual.

8 Programming within *ZEUS-3D*

One can program within *ZEUS-3D* without actually changing the master file (`dzeus36`) by the use of *change decks*, already discussed in §§2 and 7. One then directs *EDITOR* to temporarily merge the change deck into the code before (pre)compilation by including a line

```
*read <changedeck>
```

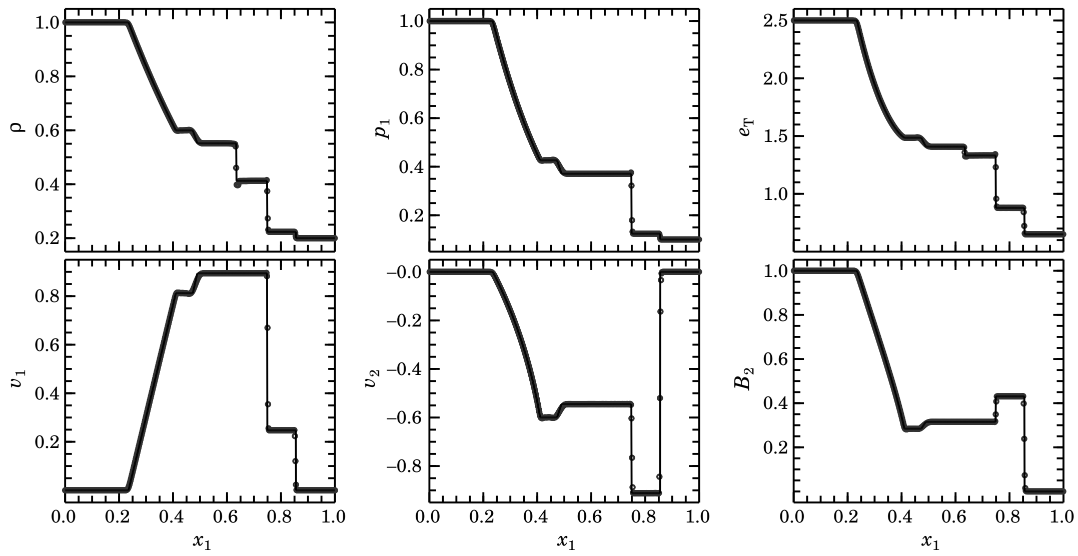
at the appropriate place in the script file `dzeus36.s`. For further details, the reader is referred to the user manual.

9 Installing *ZEUS-3D*

The public tarball, `dzeus36.tar.gz`, includes detailed instructions to install `dzeus36` and its ancillary programs and libraries on virtually any *UNIX* platform, and the reader is directed to those. This includes Windows laptops running RedHat or Ubuntu linux, MacBook Pro, and any mainframe (IBM, SUN, Cray, SGI, *etc.*). Further, `dzeus36` may be compiled by a variety of *FORTRAN* compilers including `gfortran`, `ifort`, `pgf90`, and others.

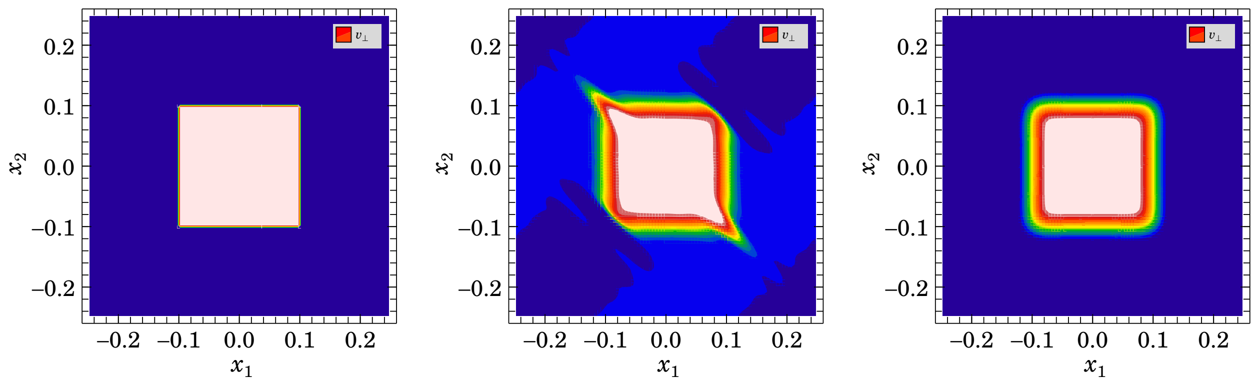
10 Example runs

1. Revisiting the 1-D shock tube example from the PRIMER ON MHD



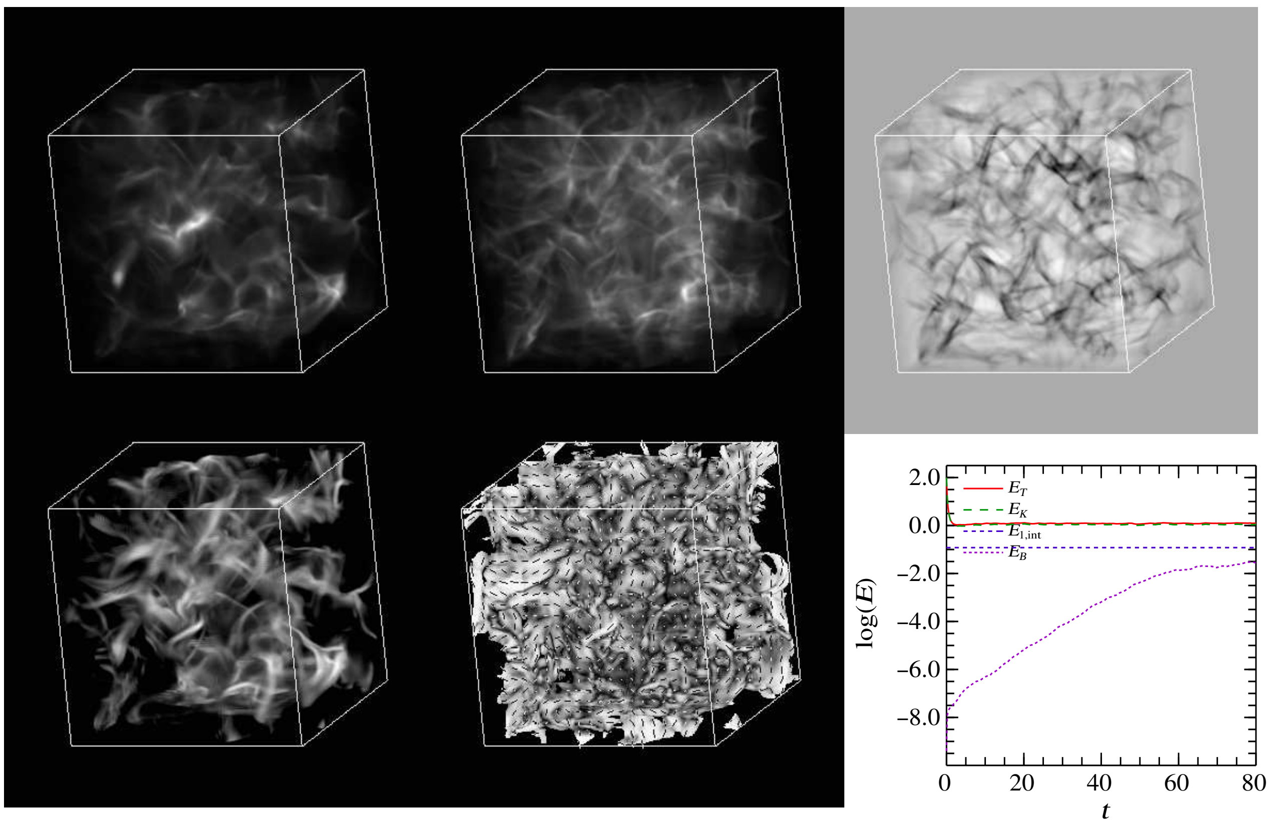
- lines are the analytical solution, bubbles are the `dzeus36` solution zone for zone.
- smooth portions of profiles accurate to within a fraction of 1% (width of bubbles)
- shocks "captured" by two or three zones
- CD captured by two zones, though there is a 1% undershoot at its base

2. 2-D transport of a square Alfvén wave



- square perturbation to $v_\perp$ (left panel) launches two oppositely directed Alfvén waves along magnetic field lines, oriented 45° from x_1-axis
- periodic boundary conditions; Alfvén waves pass through grid twice, return to origin
- without FIT (finely interleaved transport), waves develop spikes in direction orthogonal to propagation (centre panel)
- with FIT, Alfvén wave suffers only normal isotropic numerical diffusion (right panel)

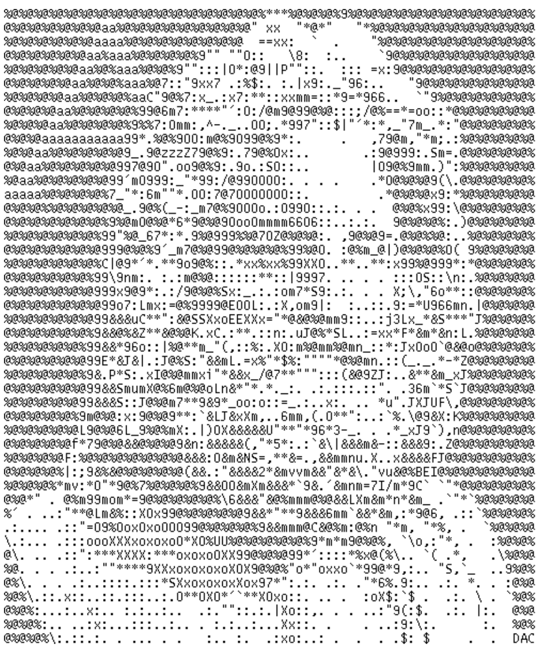
3. 3-D super-Alfvénic turbulence



This 128^3 simulation (images on next page) shows how a weak magnetic field ($\beta \sim 10^{10}$) can be boosted to equipartition ($\beta \sim 1$) in an isothermal turbulent medium, such as the ISM or in the lobes of extragalactic radio sources. This *super-Alfvénic turbulence* is a difficult simulation for MHD codes to do, and is what motivated the development of the Consistent Method of Characteristics (CMoC) in the early 1990s.

From left to right, top to bottom, the first five panels show line-of-sight integrations of: density; magnetic energy density; $\nabla \cdot \vec{v}$ (where dark lines show shocks); optically thin synchrotron emission (what a radio telescope might observe); and fractional polarisation of the synchrotron emission, including polarisation $\vec{B}$-vectors superposed. The sixth panel shows how the principle energies evolve in time, notably the magnetic energy which grows as a power law until it is saturated and in equipartition with the thermal energy density.

11 The future of *ZEUS*: AZEuS



AZEuS (Adaptive Zone Eulerian Scheme) is a marriage of Adaptive Mesh Refinement—AMR—and *ZEUS-3D*. AMR allows numerous grids of varying resolution to be automatically created or destroyed, depending on where resolution is needed. Each grid passes information to abutting ones in a completely conservative fashion, enabling simulations with much higher effective resolution than ever before.

AZEuS is still under development, and will be released into the public domain in due course. However, it has been used by us already to perform simulations of *protostellar jets*. Now, we *think* we understand how protostellar jets are launched at the sub-0.1 AU scale, but can this account for the observations of protostellar jets at the 1,000 AU scale?

You can read more about AZEuS and its maiden simulation in:

Ramsey & Clarke, ApJ, 2011, 728, L11

Ramsey, Clarke, & Men'shchkov, ApJS, 2012, 199, 13

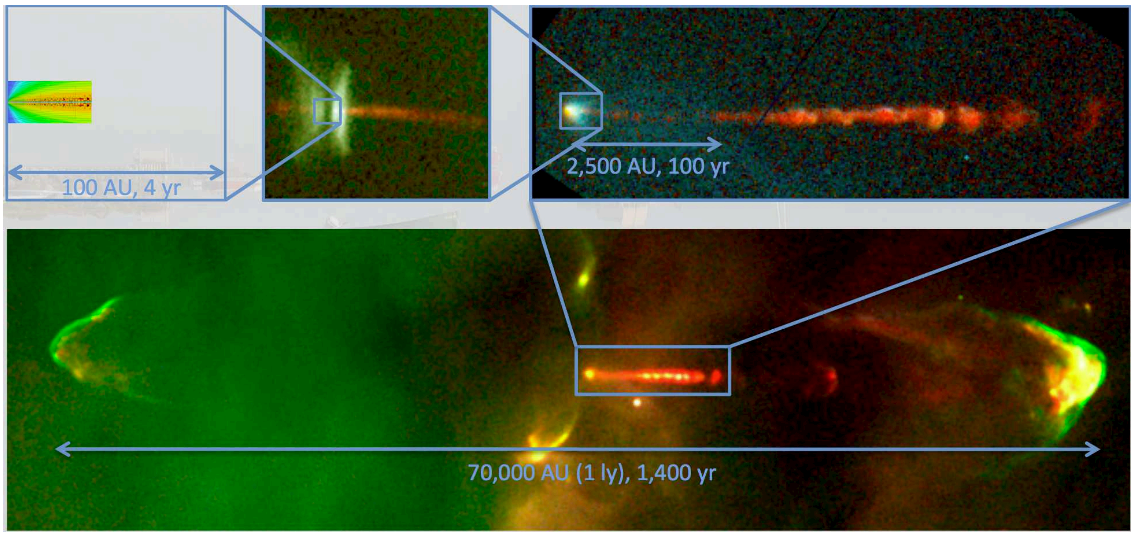


Figure 4: Inserts showing relative scale lengths of pre-AZEuS MHD simulations of protostellar jets and their observed counterparts (in this case, HH34).

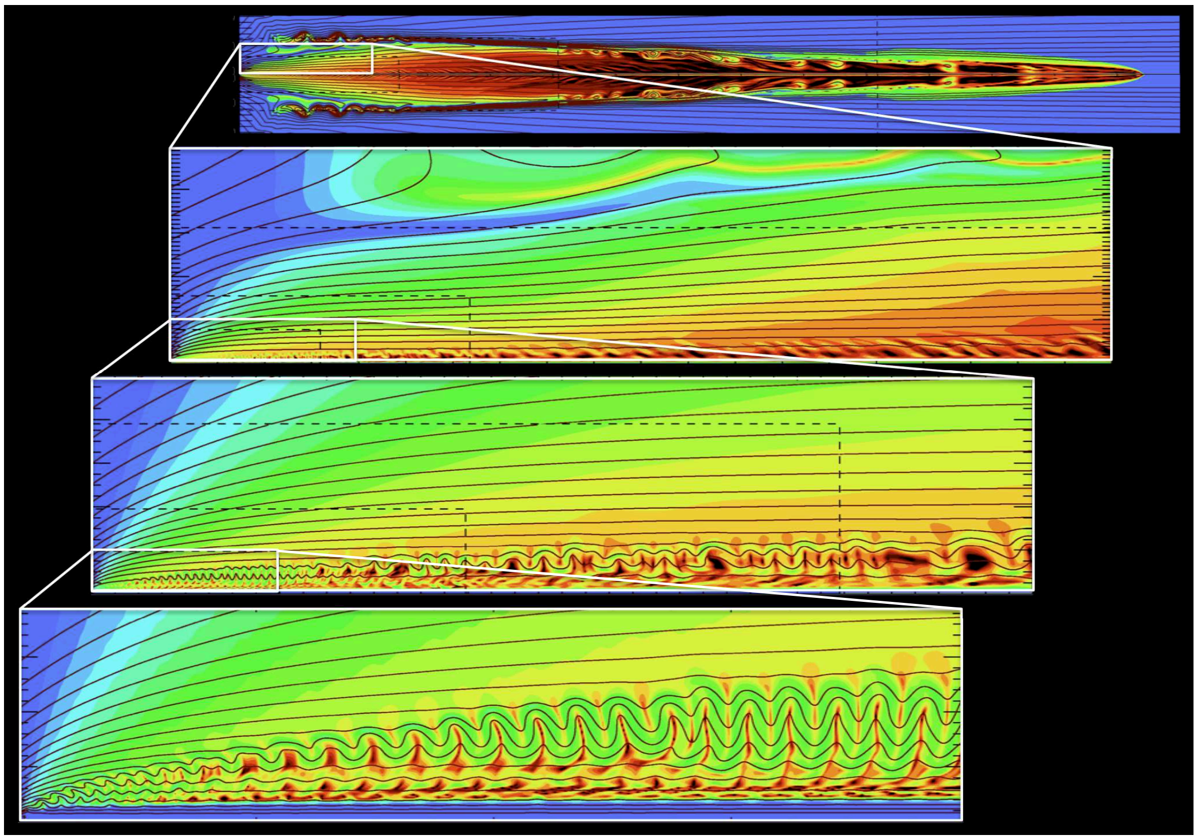


Figure 5: First AZEuS simulation: axisymmetric protostellar jets to 4,000 AU at 0.01 AU resolution. Colour contours depict the Alfvénic Mach number; contours, magnetic field lines.